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SPECIAL PAPER IN CELEBRATION OF PROF. YANG'S 50 YEARS CAREER IN MEDICINE

THIRTY YEARS IN SKULL BASE SURGERY

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The skull base generally refers to the anterior, middle and posterior cranial fossa and structures on the outside side of these skull areas. The cranial roof and skull base are separated by a line connecting the external occipital protuberance, parietal notch and supraorbital ridge [1]. The skull base supports the brain above, is connected to muscles, fascia, ligaments and bones below and contains multiple foramens and fissures, through which pass nerves, blood vessels and the medulla that are vital in maintaining life. Skull base is important for the practice of otolaryngology head and neck surgery. Diseases originating from the nose, sinuses, infratemporal fossa, roof of the nasopharyngeal cavity, parapharyngeal spaces, temporal bone, jugular foramen and craniocervical border areas can spread via communications in the skull base into the cranium or cause bone destruction and involvement of the meninges and brain. Similarly, skull base diseases can also spread inferiorly into the ear, nose and throat and severely affect patient's life and health. Due to the close relations of such diseases to important neural and vascular structures passing through the skull base and their usually deep locations, their surgical treatment carries high risks of damage to important nerves and blood vessels with potentially fatal bleeding, paralysis, cerebral herniation or even death. Damage to the brain or cerebral vessels can lead to life-threatening cerebral edema or intracranial bleeding.Surgical defects in the skull and dura compromises the normal barrier between the intracranial and ear, nose and throat spaces, resulting in increased possibility of severe complications such as cerebrospinal fluid (CSF) leak and fatal intracranial infections. Such diseases used to be considered as "untreatable" and the skull base labeled as "forbidden area". Treatment for such diseases was limited to "palliative"surgeries, radiotherapy or no therapy in the past. Since the 1970s, along with rapid progress in microanatomy, imaging diagnosis and microsurgery and development of innovative surgical instruments, together with collaboration among neurosurgeons,otolaryngologists, faciomaxillary surgeons, ophthalmologists and facial plastic surgeons, great advances have been made in the diagnosis and surgical treatment for skull base diseases in the US, Europe and Japan, making many "untreatable" diseases curable. Through the hard works by generations of surgeons in this department and great help from the neurosurgery and other departments in the PLA General Hospital, we have achieved great accomplishment in advancing the diagnosis and treatment of skull base diseases.

Modification of skull base zoning

The inner side of the skull base is divided into the anterior, middle and posterior fossa by the sphenorid alae minor and petrous bone. There are no obvious landmarks on the outer side of the skull base corresponding to the anterior, middle and posterior fossa with no standard zoning methods. Kumar et al (1986) proposed a medial and two lateral zones based on the lines from the medial pterygoid plates to the lateral points of the foramen magna. He also proposed an infratemporal zone anterior and lateral to the line between the medial pterygoid plate and temporomandibular articular fossa and a pterygotempral fossa posterior and medial to the line. Grimer divided the skull base into a medial and two lateral zones using the line between the medial point of carotid canal and inferior lamina of sphenoid bone. The medial zone contains the sphenoid body, clivus and upper cervical vertebra, while the lateral zones contain part of the sphenoid alae major, inferior portion of the temporal bone and posterior fossa. The lateral zone can be further divided into the anterior, middle and posterior sections. The anterior section expands from anterior border of the middle fossa to anterior border of petrous bone and contains foramens rotundum and ovale with the maxillary

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and mandibular nerves, foramen lacerum with the carotid artery, and foramen spinosum with the medial meningeal artery. The middle section is the petrous bone which contains internal auditory meatus and carotid canal. The posterior section comprises of the area posterior to the posterior border of the petrous bone and contains jugular foramen, foramen magna and hypoglossal foramen. These zoning criteria are not always consistent and they are complex and difficult to use in clinical practice.

Based on a study on 36 Chinese skull specimens and in consideration of clinical application, the authors proposed a skull base zoning method in 1993, which divides the outer side of the skull base into anterior, medial, lateral and posterior areas (Figure 1): 1) the anterior skull base corresponds to the anterior fossa, 2) the medial skull base is the area posterior to the anterior skull base, anterior to foramen magna and medial to extension lines from the medial sphenoid plate, 3) the lateral skull base contains the area between the inferior orbital fissure and petro-occipital fissure and lateral to the medial skull base, and 4) the posterior skull base contains the area posterior to the extension line from the petro-occipital fissure. Compared to existing zoning methods, ours provides distinct borders and clear location and area landmarks, and is useful in determining disease extent and selecting appropriate surgical approaches. Diseases in anterior and medial skull bases may be best approached through anterior frontofacial or anterior-medial approaches, and those in the lateral or posterior skull bases through lateral or posterior lateral approaches. Our zoning method has gained broad acceptance by Chinese colleagues [2].

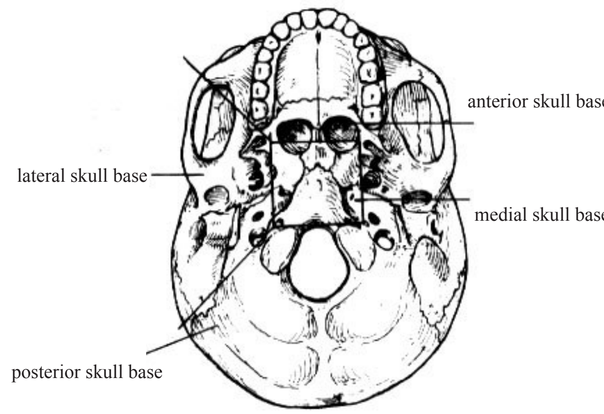


Figure 1. Skull base zoning in 1993

Pioneering studies in China on anatomy of neural and vascular structures in the lateral skull base and their clinical significance

Within the lateral skull base, there are carotid artery, jugular vein, facial nerve, lower cranial nerves and the trigeminal nerve passing through. When facing diseases in this area, protection of these important structures while resecting the lesion is a major concern for the clinician. The authors have studied the neural and vascular structures in the lateral skull base in relation to the infratemporal approach to provide anatomical knowledge for their protection.

Under the guidance of Profs. JIANG Sichang and YANG Weiyan, colored latex emulsion was injected into the arterial (red) and venous (blue) systems in 21 adult head specimens fixed with 10% formalin. The specimens were then dissected via the A or B type infratemporal approaches as described by Fisch, and the relations among the nerves and blood vessels in the jugular bulb area and structures around the carotid were studied. Results: The jugular bulbs were either rising (66.7%) or flat (33.3%). Three types of sub-petrous sinus were seen. In most cases, the IXth nerve was medial and anterior to the jugular bulb, and the Xth and XIth nerves were medial to it. The XIth nerve showed close relation to the tail of the sub-petrous sinus (Figure 2). Average distance from the carotid was 2.2 mm to tensor tympani, 6.8 mm to the middle meningeal artery and 6.9 mm to the submandibular nerve. Our study showed that the IXth, Xth and XIth nerves are closely related to the jugular bulb and sub-petrous sinus with some variations and that this anatomic knowledge is helpful in protection of important nerves during lateral skull base surgeries. The tensor tympani, middle meningeal artery and submandibular nerve are useful landmarks in predicting and locating the horizontal segment of the carotid[3]. This work has been referenced a dozen times, showing its value in guiding clinical works .

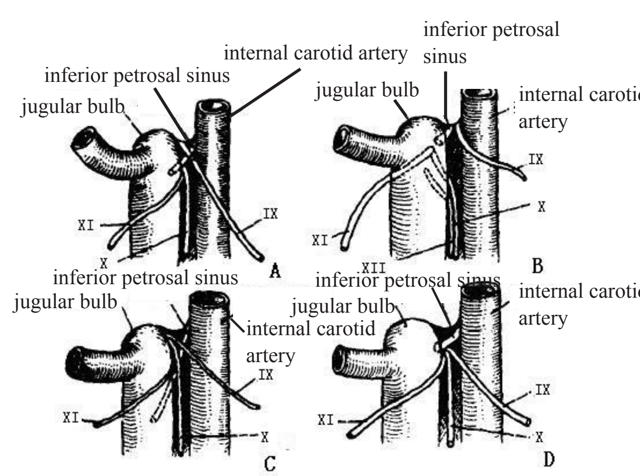


Figure 2. Variation of nerves and blood vessels near the jugular foramen

CT three-dimensional reconstruction for diagnosis and surgery planning in managing lateral skull base diseases

As imaging and computer technologies continue to advance, there is a demand for information beyond planary data when it comes to viewing complex structures in the human body. Outside China, there has been effort to reconstruct three-dimensional brain images using planary CT data. In 1996, our group became the first in China to attempt reconstruction of three-dimensional lateral skull base images [4, 5]. To investigate the value of CT three-dimensional reconstruction in lateral skull base surgeries, we studied 5 healthy adults and 10 patients with glomus tumor (n=3), acoustic neuroma (n=2), temporal bone fracture, temporal bone fibrous dysplasia, chondrosarcoma near jugular foramen, schwannoma near jugular foramen or temporal bone eosinophilic granuloma. Consecutive axial sectional images at 1.5 mm steps from the superior border of the petrous bone (or upper most point of the lesion) down to the bony landmarks of the lateral skull base (or the lowest point of the lesion) were taken on a Philips Tomoscan SR 7000 whole body scanner. Data were sent to a computer workstation running Easy Viewing for three dimensional reconstructions. Reconstructed images from the 5 healthy adults provided clear visualization of bony landmarks in this area. In patient with large lesion that had caused bone destruction, the extent of erosion and its relations to surrounding structures were clearly visible on reconstructed three dimensional images, especially regarding enlarged or eroded jugular foramen (Figures 3-5). Images could also be manipulated to simulate surgical approaches, helpful in surgery planning (Figures 6).

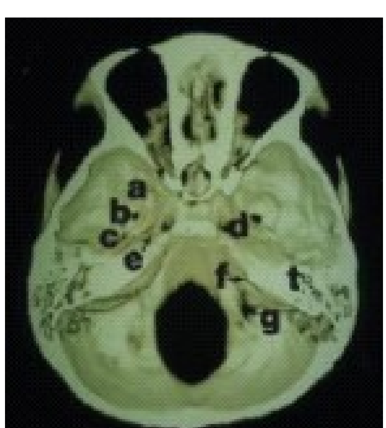


Figure 3. Internal orifice of the carotid canal as viewed on a three dimensional image of the skull base. a) foramen rotundum; b) foramen spinosum; c) foramen lacerum and internal orifice of internal carotid artery; d) trigeminal depression; e) orifice of the internal auditory meatus; f) jugular foramen; T = tegmen tympani

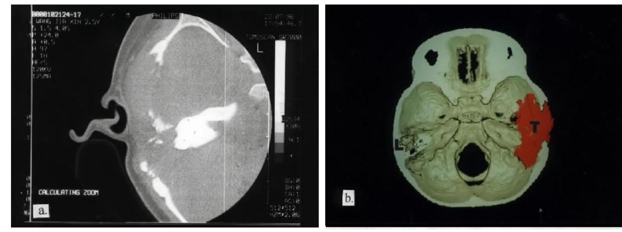
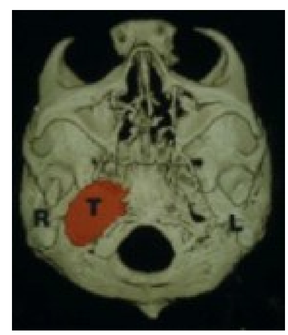


Figure 4. Right side eosinophilic granuloma. a) Regular CT image showing extensive erosion of bone. b) Three dimensional CT reconstructed image showing erosion of the tegmen tympani, squamous temporal bone and medial skull base lateral to the foramen lacerum.



(**Figure 5**)

(**Figure 6**)

Figure 5. Reconstructed three dimensional CT skull base image showing a schwannoma near the right jugular foramen.

Figure 6. Simulated left post-sigmoid craniotomy for resection of acoustic neuroma (4 cm by 4 cm). z=zygoma, m=mastoid, t=tumor.

Modification of clinical staging in skull base chordoma

Skull base chordoma mainly arises from the sphenoid-occipital junction areas. Besides its deep locations and close relations to important neural and vascular structures, it often demonstrates aggressive growth and lacks sensitivity to radio- or chemotherapies.Surgical resection is therefore the most important treatment. Because the range of tumor and involvement of intra- and extra-cranial structures vary across individual patients, classification and staging are important for accurate disease description, surgery planning and outcomes comparison. Existing classification methods are either overly complex or overly simple. In 1994, we recommended a chordoma classification system based upon the tumor location and extent of involvement, i.e. the sella, clivus, occipitotemporal and extensive chordomas [5]. The occipitotemporal chordoma is atypical as it locates outside the medial skull base, in contrast to typical chordomas. In 2003, based upon a review study on 61 cases of skull base chordomas, this classification system was further modified and a staging system was added to reflect involvement of neighboring important structures [6, 7].

Early start in skull base surgeries in China with now a complete set of surgical approaches and techniques

The authors have adopted different surgical approaches based upon the nature, location and extent of skull base diseases for best possible outcomes through relative easy resection of lesion and defect repair with minimal compromises to important structures.

In 1987, we were the first in China to adopt the "H"bilateral lateral rhinotmy for resection of bilateral upper nasal and ethmoidal lesions that extended upward to involve the anterior skull base and anterior fossa and backward to involve the medial skull base and clivus. The approach provided generous exposure and easy access to lesion areas on both sides.

In as early as 1989, led by Prof. YANG Weiyan, our group adopted the combined cranionasal approach [11]. This approach consists of a frontal and a nasal (including lateral rhinotomy and frontal/ethmoid sinusotomies) part. In individual patients, the frontal incision may be extended to form a coronal incision reaching bilateral temporal bones or a hemi-coronal incision going down the mid-line to connect to the rhinotomy incision (Figure 7). The rhinotomy incision can be modified to include the external frontoethmoidal approach, lateral rhinotomy approach and/or the "H" approach. This approach can be used in nasal and sinus lesions involving the anterior skull base, anterior fossa (with or without cerebral meningocele) and the medial skull base.

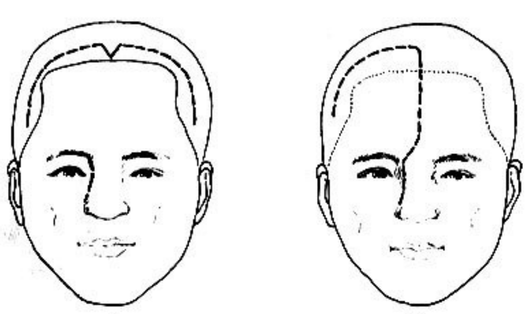
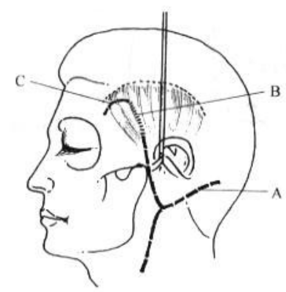
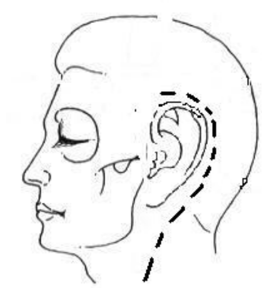


Figure 7. Incisions for cranionasal combined approach. a) frontal and rhinotomy incisions; b) connected frontal and rhinotomy incision.

In the early 1990s, our group was the first in China to adopt the Fisch A, B and C procedures. We also modified the incisions in these procedures by using a "?" or reversed "?" incision (Figure 9) to avoid ischemic necrosis of the lower auricle and minimize the risk of facial nerve injury, while in the meantime providing improved exposure of and access to lesions. These procedures are used in managing diseases near the jugular foramen, infratemporal fossa and in the lateral clivus and para-sella areas, as well as those diseases involving the petrous bone and vicinity, jugular foramen, subglossal foramen, foramen magna, dorsal clivus, apex of petrous bone and carotid canal [12-16].



(Figure 8)



(Figure 9)

Figure 8. Fisch A, B and C procedures incisions
Figure 9. Modified Fisch procedure incision

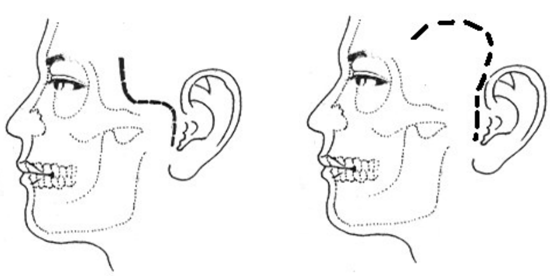
Starting in 1992, we are also the first in China to modify Holliday's procedure for improved outcomes in resection of lesions in the temporal fossa, infratemporal fossa and middle cranial fossa anterior to the petrous bone. We have extended the incision (Figure 10) upward in front of the ear to the temporalis attachment line (Figure 11) to avoid bleeding from injury to the temporal artery and transection of the temporalis. The modified incision also helps minimize the risk of injury to the temporal branch of the facial nerve and provide access to temporalis for muscle graft when needed for surgical cavity obliteration.

We started performing the Biller's procedure (i.e. mid-mandibular approach, Figures 12 and 13) in 2001. Compared to the aforementioned lateral cranial approaches, this approach provides exposure of the medial skull base aacross the mid-line, in addition to lateral portions of the skull base. With the frontofacial approach, access to lesions located in areas lateral to the mid-section skull base can be difficult, while access to the mid-section skull base can be difficult via lateral cranial approaches. The modified Biller's procedure combines the advantages from these two approaches and can be used in nasopharyngeal lesions involving pterygopalatine fossa and infratemporal fossa. It provides access to the middle cranial fossa, sphenoid sinus and cavernous sinus that can be extended across the mid-line. We have applied this procedure in 5 cases for nasopharyngeal fibroangioma, chordoma, etc, with satisfying results.

Since 2001, we have modified the middle fossa approach incision from a pre-auricular vertical linear incision to a "U" shaped incision, which provides improved exposure and reduced bleeding, as well as improved cosmetic results as most of the incision is now hidden in the hair (Figure 14).

Also in 2001, we became the first in China to perform non-defined operations for late stage recurrent tumors that involve the skull base. In most of such cases, extensive surgeries via combined approaches and radiotherapy have failed to control the disease, and the recurrent malignancy extensively involves the nose, sinuses, face, skull base, intracranial structures and important nerves and blood vessels. We have studied surgical treatment in these situations and been able to extend life and improve quality of life in some cases that are normally considered as "untreatable". We have presented systematic approach to such cases including the nomenclature, concept and techniques [17].

Minimal invasive surgeries for skull base diseases. Nasal endoscopy technology has promoted application of minimal invasive procedures in skull base diseases. Nasal endoscopy has been used by our group in repair of skull base defects, in repair of CSF leak, and in resection of cranionasal tumors and nasopharyngeal fibromas, with satisfying results [18, 19].



(Figure 10) (Figure 11)

Figure 10. Holliday procedure incision

Figure 11. Modified Holliday procedure incision

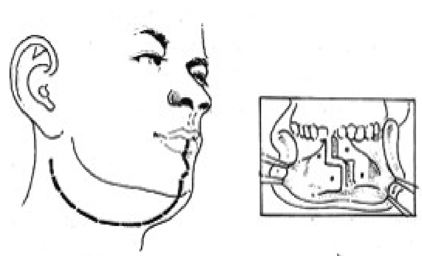


Figure 12. Biller's procedure. a) incision; b) mid-line mandibular oste

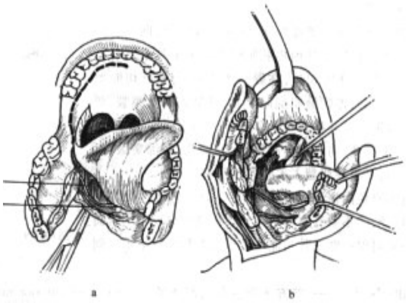


Figure 13. Biller's procedure. a) approach via the mouth floor and palate soft tissue; b) exposure of the palatine bone.

Figure 14. Modified middle cranial fossa approach incision

Frontal pediculated muscle-tendon-periostum flap for repair of sella area persistent CSF leak and skull base defects and a systematic approach in repair of skull base defects

The technique of frontal pediculated muscle-tendon-periostum flap for repair of persistent sella area CSF leak and skull base defects

CSF leak from the sella area is a common complication following trauma to the face and skull base and pituitary tumor surgeries. Repair often fails because of the deep location, difficulties in identifying the leak site and in fixing the repair material, and decay of graft over time. We have designed the frontal pediculated muscle-tendon-periostum flap technique for repair of sella area persistent CSF leak. To perform the procedure, the patient assumes a supine position. Under general anesthesia, a coronal or mid-line sagittal incision is made and a skin flap is elevated down to the supraorbital ridge. At 10 cm above the supraorbital ridge, the soft tissue is cut to the bone. A wedge shaped muscle-tendon-periosteum flap containing the supraorbital artery and frontal artery is made with a 2.5 cm wide pedicle at the brow ridge. The frontal sinus is open and the mucosa denuded. The ethmoidal cells and roof mucosa are removed via a trans-ethmoidal approach, followed by removal of sphenoid anterior wall and denudation of sphenoid mucosa. After identification of the CSF leaking site, the muscle-tendon-periosteum flap is used to repair the leak and obliterate the sphenoid cavity, reinforced by dressing. We have applied this technique in 29 cases of anterior or medial skull base defects with or without CSF leak with success in all cases.

A systematic approach to skull base defect repair

Management of bony and dura defects in the anterior and medial skull base areas:

1) Transnasal approach. Most time, the defect in the skull base bone or dura is small. In these cases, tensor fascia lata or muscle graft can be introduced through the bony defect to cover the dura defect. This is reinforced by a vomer or lamina mediana graft placed above the bony defect. Nasal cavity mucosa around the defect is carefully removed, followed by repair of the defect with tensor fascia lata graft or pediculated septum mucosa flap which is further reinforced by absorbable gelfoam and nasal cavity dressing. The authors pioneered this procedure in China. When the "H" incision is used with large dura and/or skull base defects, tensor fascia lata graft can be used to repair the dura and septum plate to repair bony defect with reinforcement using tensor fascia lata graft.

2) Maxillectomy and evisceroneurotomy approach. In case of large dura and bony defects, the dura can be repaired using a tensor fascia lata graft, which should be placed under the dura defect with an overlap of 2-3 mm. The pressure from the brain will maintain contact between the dura and graft and prevent CSF leak. The graft can be reinforced with the frontal pediculated musculocutaneous flap to increase the chance of graft survival, and the frontal donor site can be repaired using split thickness skin graft from the inner thigh.

3) Transpalatine/oral-septum-sphenoid approach. To repair sphenoid dura or bony defect, the sphenoid sinus mucosa must be denuded. The sinus cavity is then obliterated using fascia, muscle or fat graft, reinforced by gelfoam and nasal cavity dressing.

4) Transfrontal approach. The bony defect can be repaired using the bone graft taken from the inner wall of the frontal sinus or the parietal skull and the dura can be repaired using pediculated muscle-aponeurosis-periosteum flap. A pediculated soft tissue flap is then used to separate the cranium from the nasal cavity. This is the so-called “sandwich” repair.

5) Non-defined operations. Skull base and dura defects in such cases are often extensive. Repair is similar to those described above with the use of tensor fascia lata, frontal pediculated musculocutaneous flap and split thinckness skin graft for frontal donor site repair.

Management of bony and dura defects in the lateral and posterior skull base areas: Soft tissue including the muscle, fascia and skin is thick in these areas, and skull base defect often does not require specific repair. If the tympanic cavity or antrum is involved, the tegmental defect sometimes requires repair to prevent cerebral meningocele and CSF leak. Dura defect must be repaired using local temporalis flap and surgical cavity should be obliterated using pediculated muscle-fascia flap, fat or pediculated sternocleidomastoid muscle flap. Pectoralis major musculocutaneous flap can be used to repair large skin defects. Suspended facial nerve should be wrapped with pediculated muscle fascia flap to prevent ischemic facial nerve dysfunction.

Kudo clamp for resection of lateral skull base tumor involving the carotid

Malignancies in the lateral skull base area often invade the carotid, making surgical management difficult. Traditionally, tumor is partially removed from the carotid followed by radiotherapy. While the wall of carotid may slow spread of cancer cells, there is a 40% chance for it to be infiltrated by the tumor. Non-elective carotidectomy carries a mortality rate of as high as 41%. As diagnosis and research improve, there have been reports stating low mortality rate associated with elective carotidectomy, although pre-operative carotid compression sessions are needed to build collateral circulation. Carotid compression can be external or internal. External carotid compression, or Matas procedure, may not provide definite results due to collateral blood supply from the contralateral carotid via the external carotid system. Ligation or resection of the carotid solely based on Matas procedure can be very risky. Carotid grafting before removal of skull base tumor is difficult. With the Kudo clamp, stepped compression of the common carotid (with ligation of external carotid artery) or the internal carotid (no ligation of external carotid artery needed) allows establishment of compensatory blood supply by the contralateral internal carotid artery and resection of the ipsilateral carotid together with the tumor with minimal risk of severe complications such as hemi-paralysis, cerebral edema and herniation.

Digital subtraction angiography is routinely performed in our center when CT or MRI indicates involvement of the carotid in lateral skull base diseases. If the carotid is already completely occluded, it can be ligated and resected during surgery. In cases with well developed communicating arteries, relatively small lesions, good chance of preservation of the internal carotid and good Matas test results, pressure in the internal carotid upon temporary occlusion of the common carotid artery can be tested after ligation of the external carotid artery during surgery. A pressure greater than 60 mmHg (6.65 kPa) indicates sufficient cerebral blood supply from the contralateral circulation via the communicating arteries and that resection, compression or ligation of the ipsilateral internal carotid artery if necessary is probably safe. This has been done in 8 of our cases who subsequently needed resection or ligation of the internal carotid artery during surgery, with no cerebral complications. In cases with patent communicating arteries but extensive lesions involving the internal carotid artery with high probability of intraoperative compromise of the artery, the Kudo clamp can be used to build compensatory collateral circulation. Ligation of the external carotid artery will be needed if the clamp is placed over the common carotid, but not so if placed over the internal carotid artery. The clamp can be tightened one circle each day for about a week. The internal carotid artery can then be resected together with the lesion during surgery. We have used the Kudo clamp in 10 cases with no severe cerebral complications, except for transient hemi-paralysis in one case due to poor perfusion from low blood pressure related to anesthesia.

Summary

Our above mentioned accomplishments in the field of skull base surgery has greatly benefited from the deep foundation of research and clinical practice in this department. Under the leadership of Prof. JIANG Sichang, the department started building its anatomy lab, temporal bone histopathology lab, temporal bone bank, neurophysiology lab and auditory and electrophysiology lab in the 1960s. Our success has also benefited from China's "open door" policies. Senior surgeons in our group have enjoyed the opportunities to study in the US, Italy, Japan, France and UK. Upon completion of his study in the US, Prof. YANG has led the group to greatly expand surgical treatment of skull base diseases. Our achievement is also a result of the professionalism of the department leadership, which incorporates hard work, courage when facing difficulties, diligence and pragmatism. Our efforts have produced abundant fruits in the traditional "no-man's land"of skull base surgery and contributed greatly to the advance of otolaryngology, head and neck surgery, as well as skull base surgery in China.

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